USARIEM TECHNICAL REPORT T06-03

INITIAL CAPABILITY DECISION AID (ICDA) THERMAL PREDICTION MODEL AND ITS VALIDATION

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January 2006

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REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE January 2006	3. REPORT TYPE AND DATES COVERED USARIEM Technical Report

4. TITLE AND SUBTITLE
Initial Capability Decision Aid (ICDA) Thermal Prediction Model and its Validation

5. FUNDING NUMBERS

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER
T06-03

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Same as #7 above.

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The ICDA (Initial Capability Decision Aid) is a heat stress prediction model recently developed for monitoring the physiological status of Soldiers. ICDA utilizes real time input of metabolic activity derived from heart rate and air temperature. The model validation was conducted using data from three laboratory studies with varied environments (i.e., 27°C/75%RH; 49°C/18%; 35°C/45%), clothing configurations and heat acclimation status. Subjects walked on a treadmill at ~270-628 W for up to 180 min, depending upon study conditions. Root Mean Square Deviation (RMSD) between measured and predicted core temperature (Tcr) ranged between ±0.11 and ±0.50°C for these studies. The model predicted measured values of Tcr within one standard deviation, when environmental conditions were less stressful. Errors of estimates were larger with small sample size (N<5). The ICDA predictions of skin temperature were less accurate than those of Tcr. ICDA predictions of sweat rates (SR) were more accurate when environmental conditions were, in terms of heat stress, less extreme. However, for encapsulated subjects, working in a 35°C/45%RH environment, the results for predictions of SR were mixed. This model shows promising prediction of thermal status, particularly Tcr, of Soldiers during heat stress. This non-invasive model is convenient for health assessment of Soldiers required to perform different tasks for long hours.

14. SUBJECT TERMS
ICDA (Initial Capability Decision Aid), heat stress prediction model

15. NUMBER OF PAGES
40

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

DISCLAIMERS

The views, opinions and/or assertions contained in this publication are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR70-25 and USAMRMC Regulation 70-25 on the Use of Volunteers in Research. For protection of human subjects, the investigator(s) adhered to policies of applicable Federal Law CFR 46.

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EXECUTIVE SUMMARY

The ICDA (Initial Capability Decision Aid) is a heat stress prediction model recently developed for monitoring the physiological status of Soldiers. The ICDA is an abridged version of the USARIEM human thermal physiological simulation computer model SCENARIO-J (Kraning and Gonzalez., 1997) and the Gagge model (Gagge et al., 1986). ICDA utilizes real time input of metabolic activity (M) derived from heart rate (HR) and air temperature. By using HR to estimate M, Soldiers required to perform multiple tasks over extended time periods can be monitored with non-invasive sensors which are both convenient to place and comfortable to wear. This study compares ICDA predictions of core temperature (T_{cr}), skin temperature (T_{sk}), and sweat rates (SR) with laboratory measured values.

The model validation was conducted using data from three laboratory studies with varied environments (i.e., 27°C/75%RH; 49°C/18%; 35°C/45%), clothing configurations and heat acclimation status. Subjects walked on a treadmill at ~270-628 W for up to 180 min, depending upon study conditions. T_{cr} rise was restricted to <39.5°C. Individual anthropometrics, physiological and environmental time series data were collected in each study. Root Mean Square Deviation (RMSD) was utilized to examine the difference between laboratory measurements and ICDA predictions of T_{cr} and T_{sk} across time. In addition, predicted SR was compared to the measured SR where available.

RSMD of T_{cr} ranged between ±0.11 and ±0.50°C for these studies. The model predicted measured values of T_{cr} within one standard deviation, when environmental conditions were less stressful. Errors of estimates were larger with small sample size (N<5). The ICDA predictions of T_{sk} were less accurate than those of T_{cr}. Generally, model predictions of T_{sk} were more difficult than T_{cr} because measured T_{sk} varied by skin location, clothing, environmental, and operational conditions. ICDA predictions of SR were more accurate when environmental conditions were, in terms of heat stress, less extreme. However, for encapsulated subjects, working in a 35°C/45%RH environment, the results for predictions of SR were mixed.

Predictions of thermal status of Soldiers during heat stress, particularly for T_{cr}, using this simplified model, are promising. To improve predictions of T_{sk}, the existing data bases should be evaluated to determine which T_{sk} measurement site best represents the combined impact of individual variability, clothing, environment, and operations on T_{sk}, and is therefore, the best site to use for model development and validation of T_{sk} predictions. Similarly, for SR predictions, the trends of individual SR patterns need to be carefully evaluated to further refine this model. Lastly, it is recommended that ICDA be applied to real time situations in both laboratory and field training exercises for future T_{cr} sensitivity analysis, and further model development.
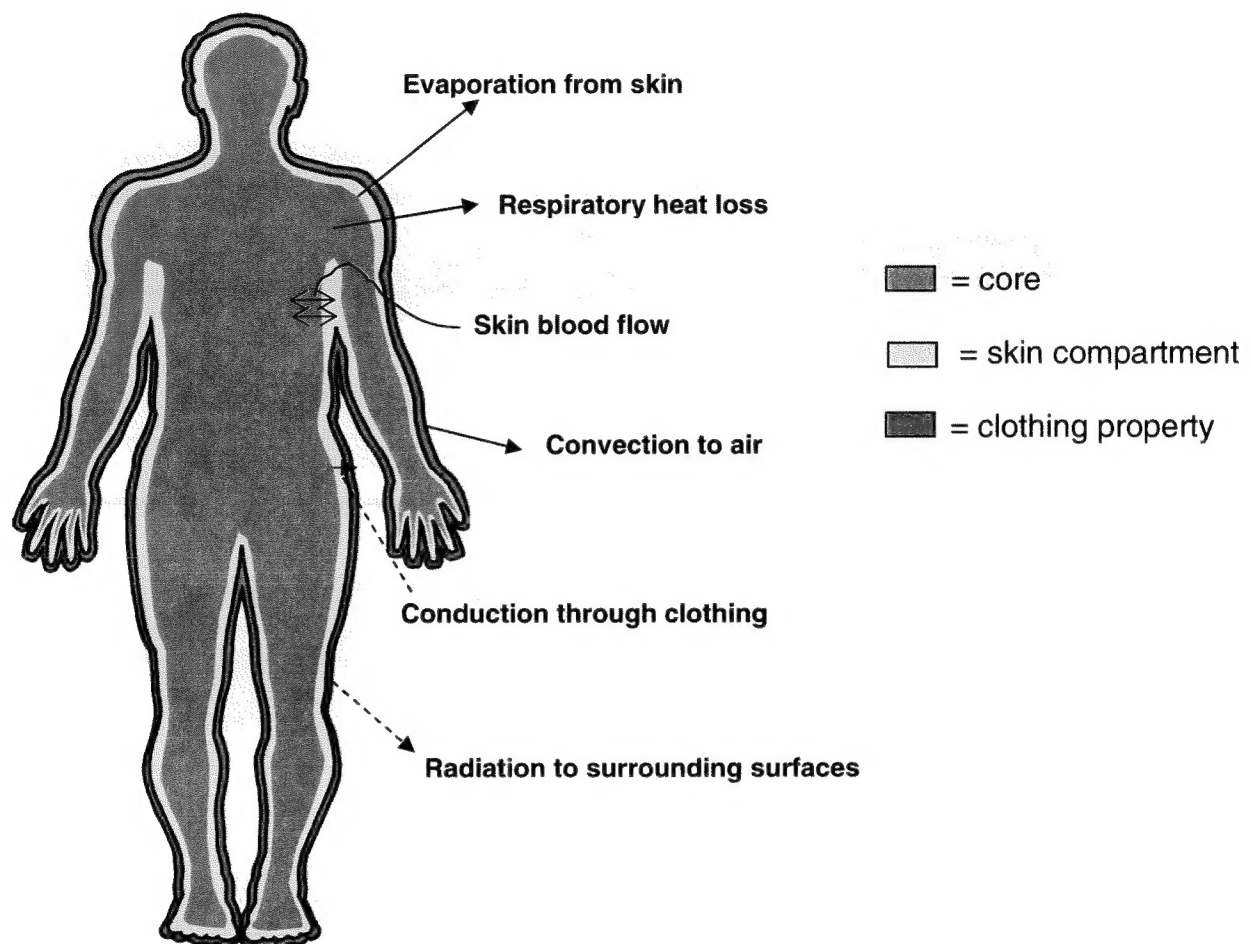
INTRODUCTION

The ICDA (Initial Capability Decision Aid) model is a heat stress prediction model recently developed for monitoring the physiological status of Warfighters. It is a basic and abridged model derived from elements of the USARIEM human thermal physiological simulation computer model, SCENARIO-J (Kraning and Gonzalez, 1997), and the Gagge Model (Gagge et al., 1986). The model can be loaded with anthropological characteristics of an individual (i.e., height, weight, and clothing), group means or use default population values. Real-time inputs of measured HR and local weather (e.g., temperatures, wind, relative humidity, estimates of radiant load) are used by the computer model to make real-time predictions and estimates of subjects' physiological status or other physiological parameters.

A main purpose for constructing this model was to predict time estimates of the internal body temperature (T_{cr}), sweat rates (SR), and hydration status of Soldiers and Warfighters in a battlefield situation. For instance, T_{cr} is the traditional and common physiological parameter for heat strain assessment as it reliably indicates impeding injury (Amos et al., 2000; Pandolf and Goldman 1978). However, measuring T_{cr} is invasive and may be impractical for real time monitoring of Soldiers engaged in long hours of various multiple and unpredictable tasks in widely disbursed hot field environment. Although obtaining "true" values of many parameters from environmental, physiological and operational conditions are desirable and increases the model's accuracy to assess Soldiers' status, alternatives for the worst case scenario (e.g., losing signals from sensor devices, wrong calibration, conflicts between sensors, etc) still need to be considered. For these reasons, ICDA was developed to predict physiological responses to battlefield situations from a minimum number of non-invasive inputs.

The thermal physiology of the ICDA model is represented schematically in Figure 1, where the human is modeled as two physiological compartments (core and skin) surrounded by a passive clothing compartment. Within a compartment the properties are uniform: i.e., everywhere in core at time t, T_{cr} has the same value. All metabolic heat production (M) occurs in the core. Some heat is lost directly from the core to the environment by respiration; all of the other heat from the core is transferred to the skin by conduction or convection with skin blood flow. The primary method used to regulate T_{cr} is achieved by controlling blood flow.

Figure 1. Schematic of core, skin and clothing compartments

Evaporation from skin

Respiratory heat loss

Skin blood flow

Convection to air

Conduction through clothing

Radiation to surrounding surfaces

■ = core

☐ = skin compartment

■ = clothing property

The basic ICDA operational structure is summarized in Figure 2. The outline identifies the simulation routines used to predict an individual's T_{cr}, sweat rate, accumulated water loss (WL), skin temperature (T_{sk}), metabolism, and a thermoregulatory strain indicator quantified by the physiological strain index (PSI) (Moran et al., 1988).

Figure 2. Basic operational structure of ICDA
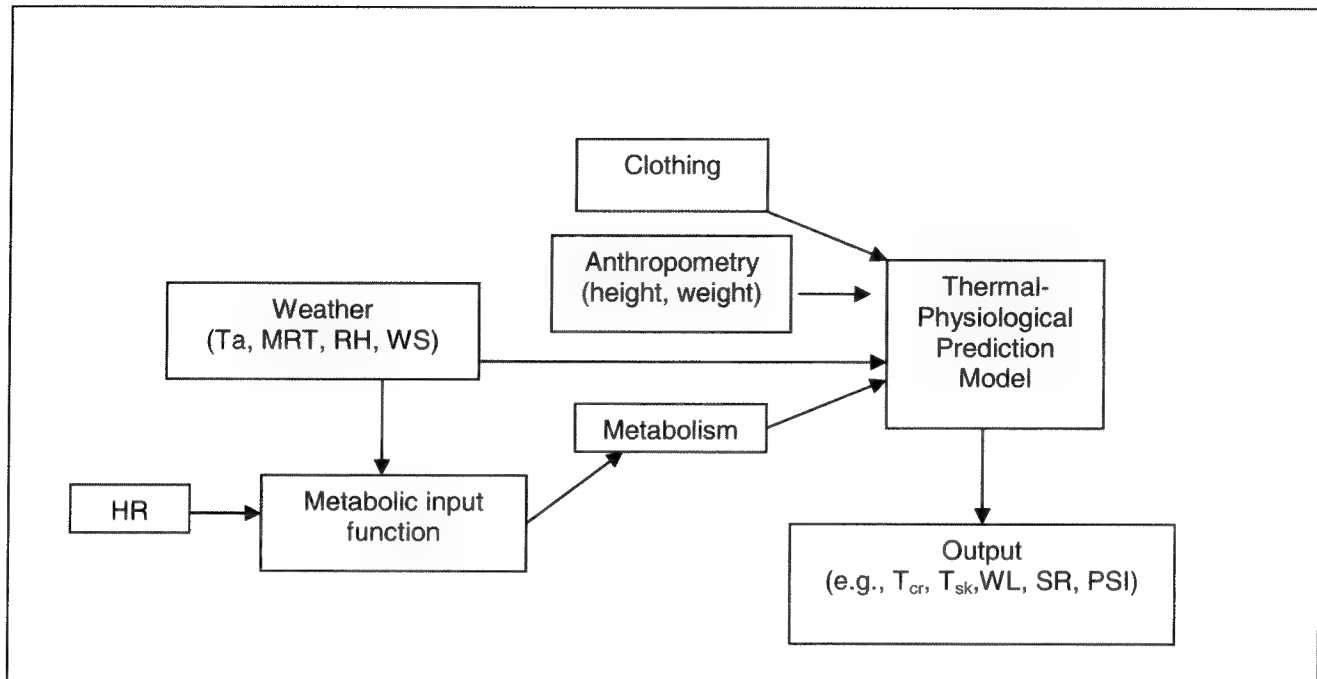
Recent reports from wars in Iraq and Afghanistan indicate that faster access to medical/surgical care and identifying evacuation situations would save more Soldiers' lives (Bilski et al., 2003; Gawande, 2004). The current strategies to shorten the time lag between injury and treatment is to position a small surgical care unit near the battlefield (Bilski et al., 2003). The model can contribute this effort by forecasting both real-time and future probabilities of Soldiers' health status by notifying unit medical personnel and command elements on the battlefields. The ICDA will also provide a longitudinal projection of SR, which can be used to predict Soldiers' dehydration status and water requirements. SR predictions are important for both logistics and for Soldiers to assess unit and individual water requirements (Montain et al., 2005). Thus, logistics personnel can plan for water delivery to meet the projected demand and the associated cost, and Soldiers can sustain their physical and cognitive performance by preventing from dehydration.

This study described the basic concept of the ICDA model, and presents an evaluation of model performance with a focus on T_{cr}, T_{sk} and SR predictions using available data from military heat studies. Comparisons of measured physiological data with the model predictions provide the analytical basis needed to characterize model performance and, if necessary, identify further improvements of the model.

METHODS

ICDA MODEL

The ICDA model as described in the Introduction represents the human by two active physiological compartments (core and skin) surrounded by a passive clothing compartment. The model was designed for military personnel, who routinely are heat acclimatized and have normal or low levels of body fat relative to the general population.

Metabolism (M): The source of heat production in the core compartment is metabolic activity. Thus, M is an important parameter for estimating T_{cr} and T_{sk}. Real time estimates of M for input into the ICDA model are derived from the Soldiers' measured HR and environmental temperatures (Berglund, 1977) using the following equation:

$$M = [0.68+4.69 \bullet (HRratio-1) - 0.052 \bullet (HRratio-1) \bullet (T_a-20)] \bullet 58.1 \bullet Adu \quad [W] \quad (1)$$

where HRratio = observed HR given at the time divided by the resting HR of the individual, and T_a = ambient temperature in °C. Adu is the body surface area. The basis for Equation 1 is that M as HR increases for a given task at an elevated T_a. The heart pumps blood to transport oxygen to the cells to support the metabolic effort and to exchange heat at the skin in order to cool the core. This increased HR to the skin is a non-metabolic activity. The metabolic adjustment for T_a in Equation 1 corrects HR for the non-metabolic cooling function of skin blood flow.

This equation is applicable for the conditions including $20°C \leq T_a \leq 40°C$, $1.2 \leq HRratio \leq 2.1$, wind speed $\approx 1.25 \text{ ms}^{-1}$, dew point temperature $\leq 20°C$, and an intrinsic clothing insulation of about 0.6-0.7clo (i.e. that of a BDU). Within these limits, a good relationship exists between HR and O_2 uptakes for different work rates in laboratory studies (Berglund, 1977). HR is non-invasive and convenient to measure compared to T_{cr}, particularly for long-duration duty assignments.

Heat balance: A heat balance analysis of the core compartment yields,

$$M/Adu=qres+qk+qskbf+(Wc/Adu) \bullet cbt \bullet (dT_{cr}/dt) \quad [W/m^2] \quad (2)$$

where
Adu = the body surface area
qres =respiratory heat loss
Specific heat of body tissue (cbt) is constant as .97W•h/°C•kg, and
Wc = the weight (kg) of core.
Passive heat conduction (qk) from core to the skin $=k \bullet (T_{cr}-T_{sk})$
Conductance (k) of tissue between core and skin = 5.28W/(°C•m²).
the heat transported by blood flow (qskbf) to the skin $=Skbf \bullet cpb \bullet (T_{cr}-T_{sk})$,
    Where specific heat of blood (cpb) = 1.163 W•h/(L•°C).

Skin blood flow (Skbf) = $[Skbfn + Cdil \cdot (T_{cr} - T_{cset})]/(1 + C_{str} \cdot (T_{skset} - T_{sk}))$
where The vasolidation coefficient (Cdil) = $50 L/(h \cdot m^2 \cdot °C)$
The neutral Skbfn = $6.3 L/(h \cdot m^2)$,
vasoconstriction coefficient, C_{str}, = $0.5 °C^{-1}$.
T_{cset} = $36.8°C$, and T_{skset} = $33.7°C$.

Skbf is modeled proportional to changes in T_{cr} and T_{sk} from set point temperatures (T_{crset}, T_{skset}). The maximum and minimum Skbf limits were set to 90 and 2 L/min, respectively.

The rate of T_{cr} change (T_{cr}/dt) found by rearranging Equation 2:

$$T_{cr}/dt = (M/Adu - qres - qk - qskbf)/(Wc \cdot cbt/Adu), \qquad (3)$$

can be step-wise integrated to find the next T_{cr} (T_{cr2}) after time step (Δt):

$$T_{cr2} = T_{cr1} + [dT_{cr}/dt]_1 \Delta t \qquad (4)$$

In a similar fashion, the energy balances of the skin compartment can result in:

$$qskbf + qk = qdry + qevap + Wsk/Adu \cdot cbt \cdot (dTskc/dt) \qquad (5)$$

where qskbf and qk represent conduction and blood flows from the core to skin. Dry heat flow from the skin to the clothing compartment is qdry, and qevap is the evaporative heat losses from the skin. Wsk represents the weight (kg) of skin.

As with the core compartment, the rate of change of skin temperature in the compartment determined from the energy balance can be stepwise integrated to find the compartment's skin temperature at time $t+\Delta t$.

Heat transfer: The model of heat exchange between the human skin surface, clothing and environment is defined by functions for effective air movement, resistance to heat flow by radiation and convection, and the resistance to evaporative heat transfer (Kraning and Gonzalez, 1991). This dry heat loss (Dry) was determined by:

$$Dry = (T_{sk} - T_o)/(R_{clt}) \qquad [W/m^2] \qquad (6)$$

where R_{clt} is the total dry thermal resistance between skin and the environment and T_o is the operative temperature. R_{clt} values used in the ICDA validation process are from thermal manikin measurements for the specific clothing ensembles used in this model. T_o is defined as:

$$T_o = (hc \cdot T_a + hr \cdot T_r)/(hc + hr) \qquad [°C] \qquad (7)$$

where T_a and T_r in Equation 7 represent air and radiant temperatures, respectively. The hr and hc terms are the coefficients of radiant and convective heat transfer, defined by the following two equations:

$$hr = 4\sigma \bullet (A_r/A_D) \bullet \left[\frac{Tcl + To}{2} + 273 \right]^3 \quad [W/(°C \bullet m^2)] \qquad (8)$$

$$hc = 8.6 \bullet V^{.53} \quad [W/(°C \bullet m^2)] \qquad (9)$$

where σ is the Stefan-Boltzman constant known as 5.67×10^{-8} [W/(m²•K⁴)], and A_r/A_D is the of body surface fraction exposed to radiation equal to about 0.725 for a standing person. For low wind (V in m/s) conditions, hc is estimated from metabolic activity (see Appendix A for details).

The total respiratory heat loss is the sum of the evaporative respiratory loss (E_{res}) (Fanger, 1972) and convective respiratory loss (C_{res}). They are related to exercise intensity at a given environment (Kraning and Gonzalez, 1991):

$$E_{res} + C_{res} = 0.0023 \bullet M \bullet (44 - P_a) + 0.0014 \bullet M \bullet (34 - T_a) \quad [W/m^2] \qquad (10)$$

where M is total metabolic activity in watts (W) ; P_a is ambient vapor pressure; and T_a is air temperature.

Quantitatively, relative to respiratory heat loss, heat loss from the skin surface is much more significant. The maximum rate of evaporative heat loss (E_{max}) from the skin surface is calculated based on the vapor pressure difference between skin surface and air:

$$E_{max} = (P_{sk} - P_a)/R_{pclt} \quad [W/m^2] \qquad (11)$$

where P_{sk} = saturated vapor pressure (T_{orr}) of water at skin temperature; P_a = ambient vapor pressure; and R_{pclt} = total vapor resistance of the clothing from skin to ambient. R_{pclt} values used in this validation study report were measured by a sweating thermal manikin for the specific clothing ensembles used in this model.

Sweat rates (SR): The sweat rate (SR) for evaporative heat loss is modeled as being proportional to changes in mean body temperature(T_{mb}) and skin temperature from set point values:

$$SR = 170 \bullet (T_{mb} - T_{mbset})e^{-((Tsk - Tskset)/10.7)} \quad g/(h \bullet m^2) \quad [g/min] \qquad (12)$$

where the set point of Tmb, $T_{mbset} = 36.49°C$ and $T_{skset} = 33.7°C$

Evaporative heat loss (E_{sk}) is calculated from skin wettedness (w), the fraction of the skin covered with sweat, and the maximum evaporation rate (E_{max}) of 100% wet skin:

$E_{sk} = w \cdot E_{max}$, where $w = SR \cdot hfg / E_{max}$ and hfg is latent heat of evaporation (=.68 W·h/g). If $SR \cdot hfg > E_{max}$, $w=1$ and excess sweat drips off the skin. For the validation modeling, the maximum sweat rate was limited to 667 g/(h·m^2).

PSI: In addition to T_{cr}, T_{sk}, and SR, the ICDA also calculates the Physiological Strain Index (PSI). PSI combines HR and T_{cr} values at any given time to provide a simple, concise and ordinal physiological strain scale between 0 and 10. PSI has been useful to evaluate heat strain in relation to various combinations of environmental (e.g., heat, humidity), operational (e.g., clothing, work rates) and biological (i.e., gender) conditions (Moran et al., 1988). The PSI was calculated as follows (13):

$$PSI = 5(T_{crt} - T_{cr0}) \cdot (39.5 - T_{cr0})^{-1} + 5 \cdot (HR_t - HR_0) \cdot (180 - HR_0)^{-1} \quad (13)$$

where T_{cr0} and HR_0 are the initial T_{cr} and HR measurements at rest, and T_{crt} and HR_t are simultaneous measurements at a given time (*t*).

The details of the physiological, thermodynamic and heat transfer functions of the ICDA are described further in APPENDIX A.

VALIDATION DATA

The model validation was conducted using three laboratory heat studies. The investigators adhered to the policies for the protection of human volunteers as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 45 CFR Part 46. Test volunteers provided their informed consent prior to participation in the study and were free to withdraw from the study at any time.

Heat Study1 (HS1): Nine volunteers (8 males, 1 female; age: 23 ± 4 [SD] yr; height 174.2 ± 5.2 cm; weight: 73.4 ± 6.5 kg; Body Mass Index (BMI): 24.2 ± 1.6), wearing hot weather battle dress uniform (HWBDU) did intermittent exercise in a warm-humid environment (27°C,75%RH) for 170 minutes (Santee et al., 2005) , The exercise routine consisted of walking on a level treadmill at 1.34 ms^{-1} for 30 minutes followed by 10 minutes of rest. These individuals were not heat acclimated prior to the study. The study conditions were relatively benign and no subjects were withdrawn due to pre-set physiological safety limits (Santee et al., 2005). T_{cr} was measured rectally and the skin surface temperature was averaged from 3 regions (back, arm, thigh) measured by heat flow discs (Santee et al., 2005). The average T_{sk} was calculated utilizing Burton's weighting method ($0.5 \cdot T_{back} + 0.36 \cdot T_{thigh} + 0.14 \cdot T_{arm}$) (Santee et al., 2005).

Heat Study2 (HS2): Seven male Soldiers, wearing Army Physical Fitness Uniform (APFU) (i.e., T-shirt, shorts, socks, shoes), continuously walked on a treadmill with a 4% grade at 1.56 m·s^{-1}. Metabolisms ranged from 420 – 620 watts in a hot dry (49°C,18%RH) condition (Montain et al., 2005). The maximum exercise duration was 100 minutes and subjects discontinued a test at a point of their voluntary exhaustion or $T_{cr} > 39.0$°C. Subjects (age: 22 ± 5 yr, height 176 ± 4 cm; weight: 71.1 ± 9.3 kg; BMI: 22.9 ± 2.4) were un-acclimated on the 1st day of the study. The experiment was

repeated daily for 10 days (Montain et al., 2005). Only five volunteers participated on the 10th day. The data, collected on the 1st day (non-acclimated stage) and 10th day (acclimated stage), were utilized in this study. An ingestible telemetry temperature pill was utilized to measure T_{cr}. Skin temperatures were measured by thermocouples from four regions (i.e., chest, forearm, thigh, and calf) to calculate a mean weighted T_{sk} based on Ramanathan (1964) method described as $0.3\bullet (T_{chest}+T_{arm}) + 0.2\bullet (T_{thigh}+T_{leg})$ (Montain et al., 2005).

Heat Study3 (HS3): Eight heat acclimated men (age: 23 ± 6yr; height: 176 ± 6 cm; weight: 76.0 ± 15.4 kg; BMI: 24.4 ± 4.3), wearing chemical protective garments, walked on a treadmill with a 4-9 % grade at $1.56\text{-}1.65\text{m}\bullet\text{s}^{-1}$. Metabolic effort averaged 450W and oxygen uptake was ~55% of Vo_{2max}. Participants walked until they voluntary withdrew from the study or $T_{cr} > 39.5°C$ (Latzka et al., 1998). Subjects were able to continue exercising for < 40 minutes at 35°C/45%RH. Their physical characteristics (mean $\pm$ SD) including age and anthropometry were: 23 ± 6 yr, height: 174.2 ± 5.2 cm; weight: 73.4 ± 6.5 kg (Latzka et al., 1998). T_{cr} was measured rectally. T_{sk} was measured by thermocouples at four sites (i.e., forearm, chest, thigh, calf) and mean T_{sk} was calculated based on Ramanathan (1964) weighting method (Latzka et al., 2005).

Table 1 shows the summary of these three studies. Depending upon the study schemes, HR, T_{cr}, and T_{sk} were collected at different time intervals. Volunteers in all studies exercised without water replacement. Sweat rates were measured in HS1 and HS3, calculated by the difference in body weight and associated weights (i.e., clothing) between before and after work. If resting HR was not available, a default value of 70 bpm was used as the model input; otherwise actual HR of subjects who were resting or sitting at the beginning of the studies or the lowest HR during the studies was utilized as resting HR. In addition, if measured HR values during more active phases were missing, values interpolated over the time interval between existing data points were substituted. The HR summary in each study is displayed in APPENDIX B.

Table 1. The data summary used in this study

Study#	HS1	HS2	HS3
Ta ($^{\circ}$C)	27	49	35
RH (%)	75	18	45
Acclimation Status	No	No-->Yes	Yes
Clothing	HWBDU	T-shirt & Shorts	Protective clothing
Activity (W)	277-350	412-628	343-552
Duration (min)	~170	<100	<40
n	9	7	8
Source	Santee et al., (2005)	Montain et al., (2005)	Latzka et al., (1998)

STATISTICAL ANALYSIS

The predicted and observed T_{cr} and T_{sk} were compared using Root Mean Square Deviation (RMSD) in each individual. The RMSD was used to quantify the average difference between predicted and observed measurements across time (4).

The RMSD was calculated as follows:

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}d_i^2} \qquad (14)$$

where d_i = difference between observed and predicted at 1-min intervals; and n = the number of compared points.

In addition, Evaporative Sweat Rates (EvapSR) predicted by the ICDA model were compared with measured EvapSR in available studies, using a paired t-tests.

RESULTS

CORE TEMPERATURE

Figure 3 (a-d) summarizes the comparisons of mean measured T_{cr} to the corresponding mean ICDA predictions. RMSD ranged between 0.11 and 0.50 °C for these studies. The model predictions were within one standard deviation of the mean measured values, when T_{cr} of the volunteers, wearing BDU and walking at 27°C /75% environmental conditions, were less than 38.0°C (e.g., Figure 3a). For the HS2 data, prediction errors were greater in non-acclimation subjects than in acclimated subjects at 49°C/18% (e.g., Figure 3b and 3c). Although T_{cr} in unacclimated individuals in HS2 quickly reached very high levels (> 39.0°C) (Figure 3b), after the 10-day heat acclimation process, the same individuals were able to maintain their T_{cr} at a lower level (~38.5°C) (Figure 3c). Initially, for heat acclimated Soldiers at 49°C/18%RH, the model predicted a rate of increase in T_{cr} greater than that measured; however, the model was more accurate toward the end of exercise (Figure 3c).

Errors of estimates were also larger when sample sizes, due to the voluntarily terminations, were smaller (n<5) (e.g., Figure 3b, 3d). However, ICDA predictions were reasonable for HS3 in which subjects, wearing protective garments and walking in a hot humid condition, increased their T_{cr} < 39.5°C.

Figure 3 The summary comparisons between mean measured and predicted core temperature (T_{cr}) from different heat studies.

a. Heat Study 1 (27°C, 75%; hot weather battle dress uniform; n=9)
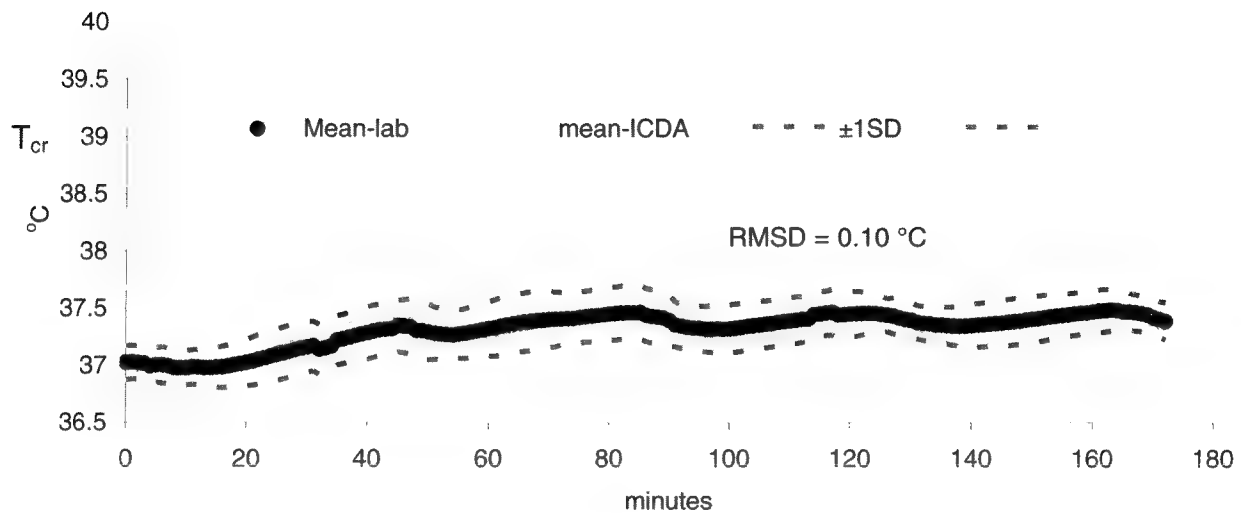
b. Heat Study 2 (day1 – non acclimation state; 49°C, 18%; army physical fitness uniform; n≤7)

Figure 3 cont.

c. Heat Study 2 (day10 – heat acclimated state; 49°C, 18%; army physical fitness uniform; n=5)
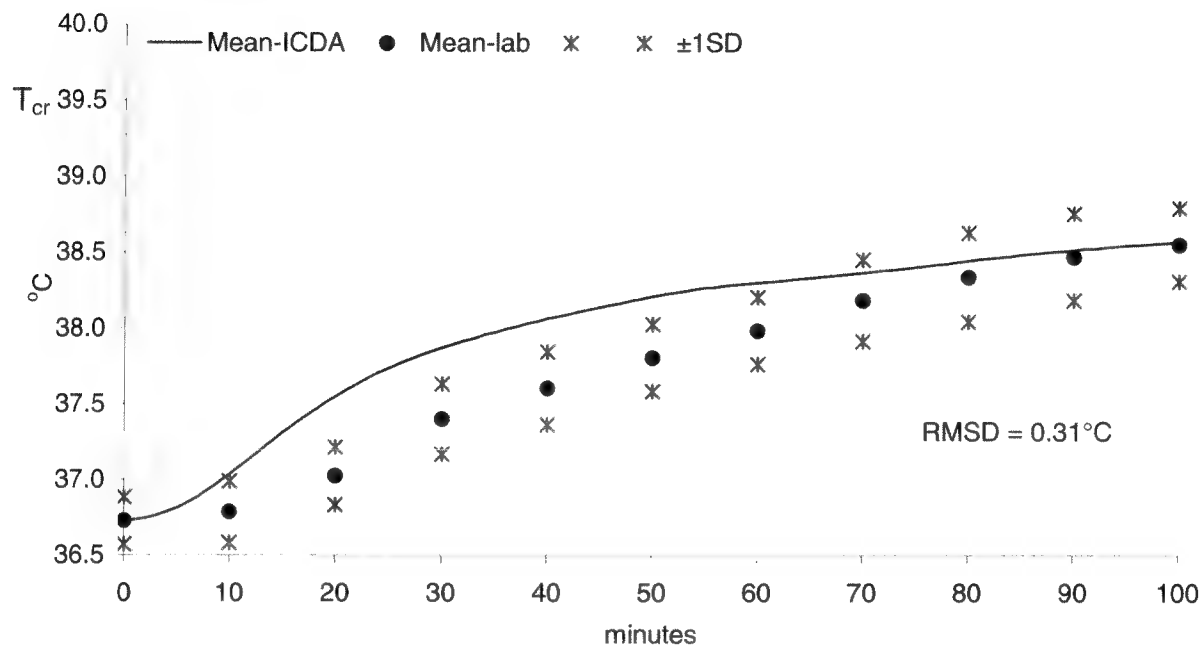
d. Heat Study 3 (35°C, 45%; protective garment; n≤8)
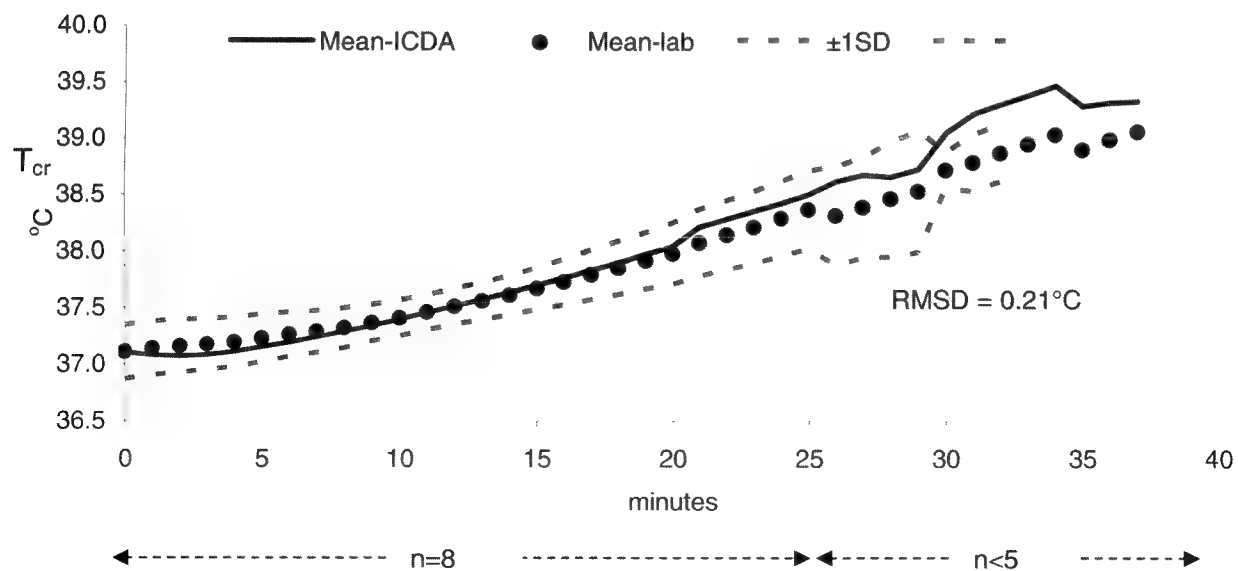
SKIN TEMPERATURE

The results of ICDA predictions for T_{sk} varied between the different studies. T_{sk} measurements on the 1st day in HS2 were not available. Overall, in comparison to the T_{cr} predictions, the model predictions of T_{sk} were less accurate. Figure 4 (a-c) shows the comparisons between measured T_{sk} and the model predictions for the three studies. In all studies, the model tended to over-predict the measured mean weighted T_{sk} (Figure 4a-c). In comparison to the other studies, predictions for HS3 (Figure 4c) showed better agreement with measured mean weighted T_{sk} (RSMD = 0.64°C). During HS3, volunteers wore protective clothing which limited evaporative heat transfer through clothing to the environment. In contrast, for HS1 and HS2 (Figure 4a, 4b), the model tended to over-predict measured mean weighted T_{sk} by about 1 °C or more.

Figure 4. Comparisons between mean measured and predicted skin temperature (T_{sk}) for three heat studies.

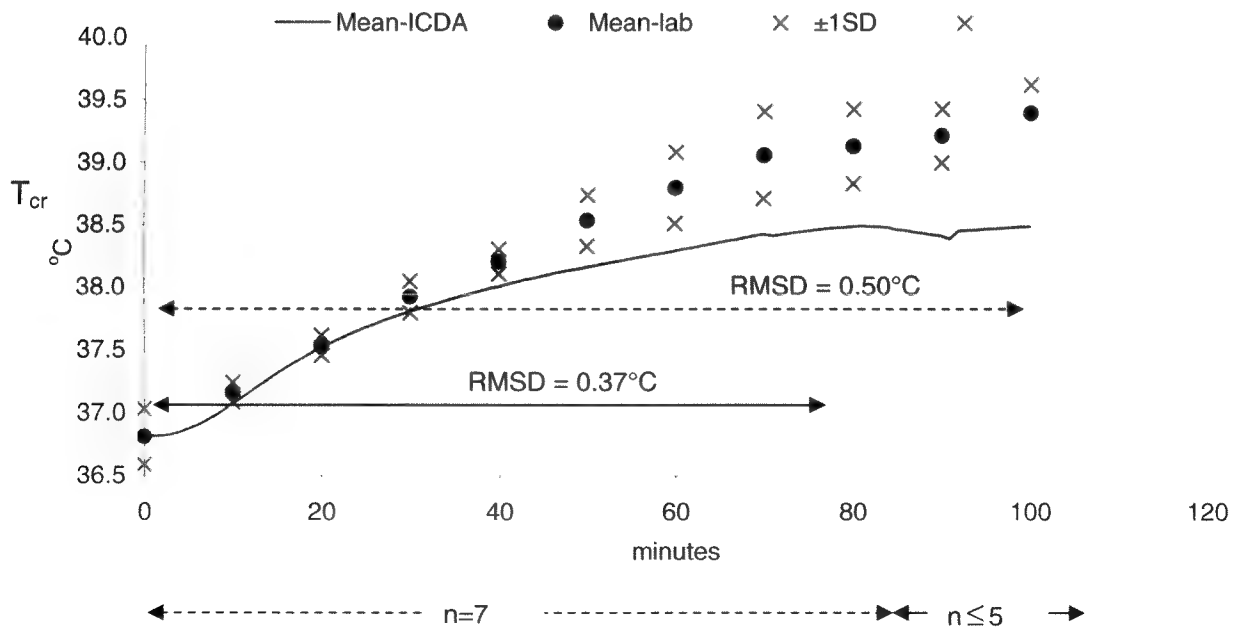a. Heat Study 1 (27°C, 75%; hot weather battle dress uniform; n=9)
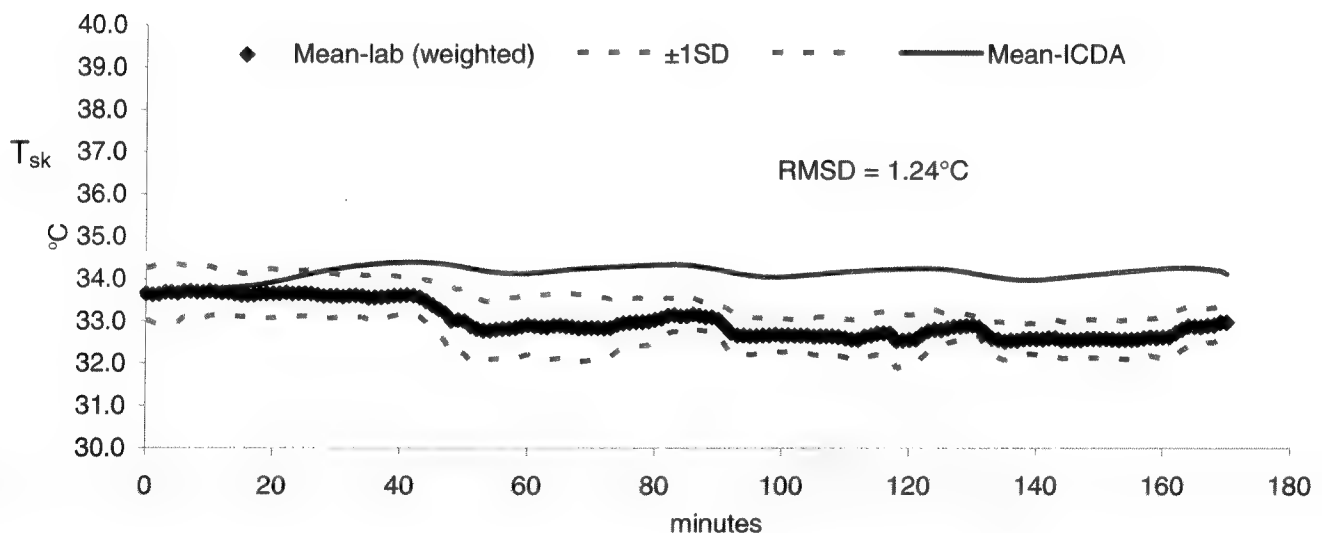
Figure 4 cont.

b. Heat Study 2 (day10 – heat acclimated state; 49°C,18%; army physical fitness uniform; n=5)
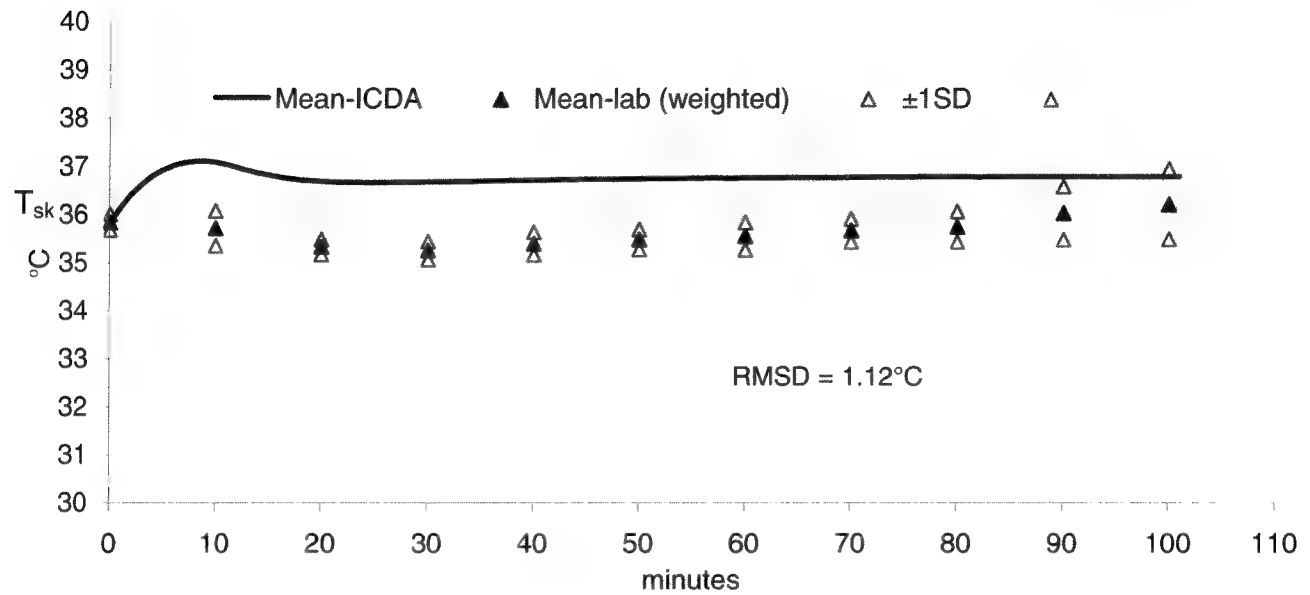
c. Heat Study 3 (35°C, 45%; protective garment; n≤8)
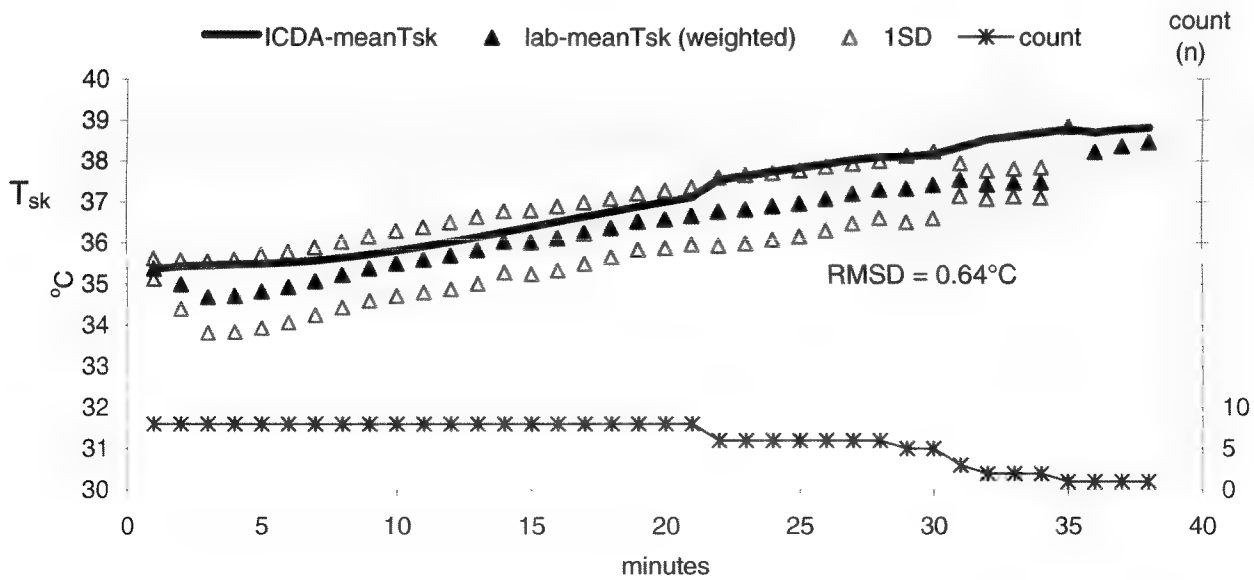
Accurate predictions for T_{sk} were problematic because measured T_{sk} varied by skin locations and between individuals. Figure 5a and Figure 5b are examples of regional T_{sk} collected from two volunteers in HS1. The first individual's thigh temperature (T_{thigh}) (Figure 5a) agreed closely with predicted T_{sk}. However, the back (T_{back}) and arm (T_{arm}) temperatures were cooler after 30 minutes and the deviation between observed and predicted values for the arm increased with time. The second subject's T_{thigh} (Figure 5b) also agreed well with the predicted T_{sk}. The T_{back} was similar to T_{arm} until the T_{arm} sensor became detached during the final 140-160 minute.

Figure 5a. The distributions of measured skin temperatures by different regions and ICDA predictions in one individual (SN7) from HS1: Example 1.
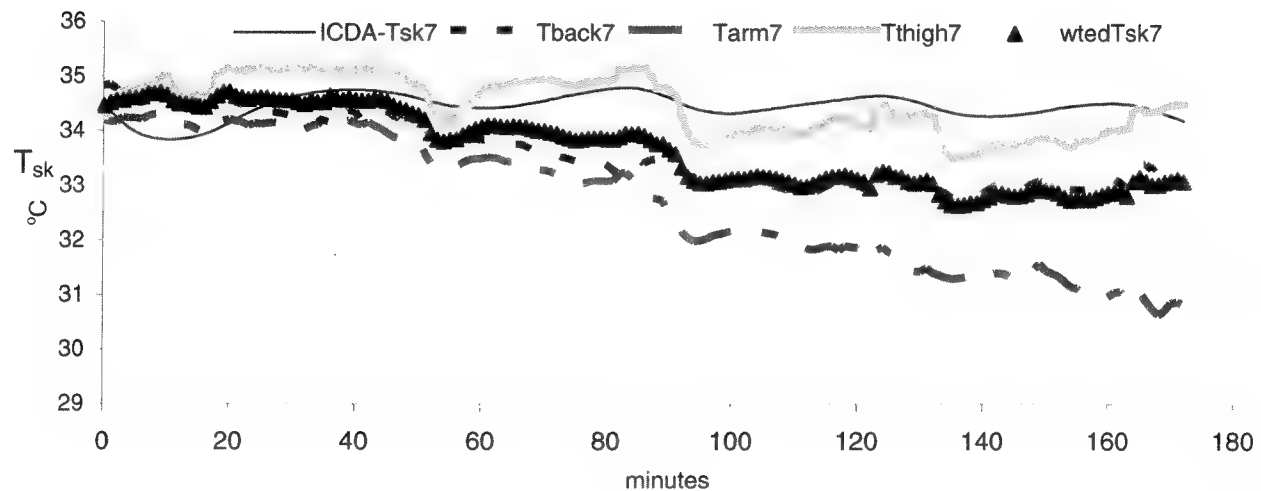
Figure 5 cont.

Figure 5b. The distributions of measured skin temperatures by different regions and ICDA predictions in one individual (SN4) from HS1: Example 2.
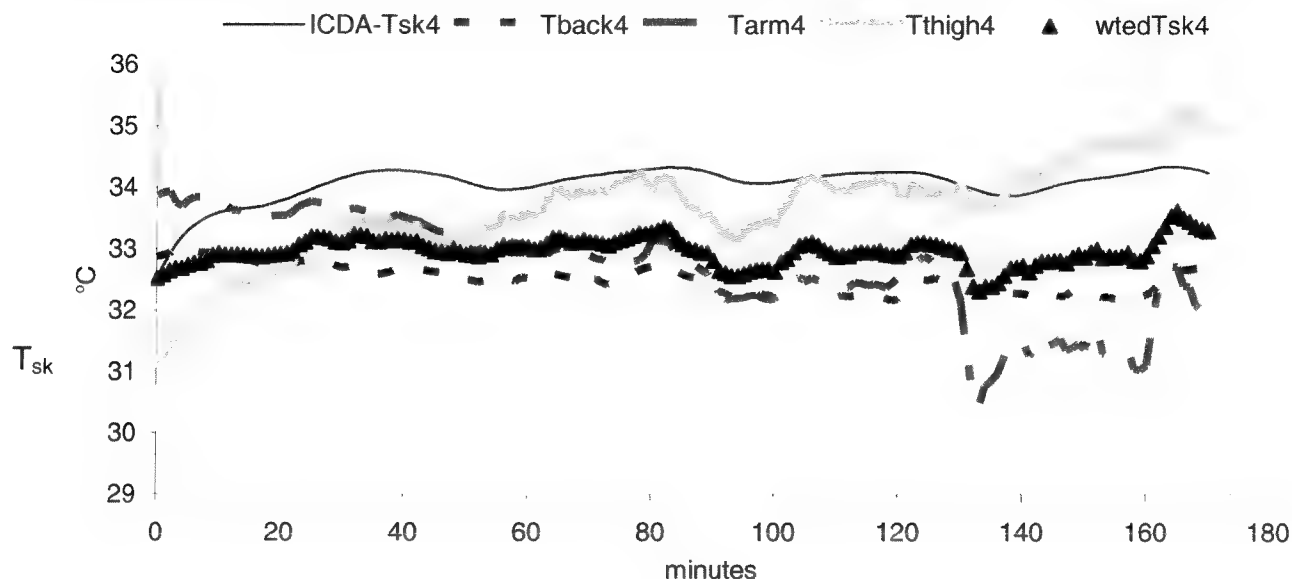
As opposed to the various T_{sk} responses in HS1 (Figure 5a, b), the responses of T_{sk} by region were relatively uniform in HS3 when subjects, wore protective garments.

Figure 6a and 6b are examples of measured T_{sk} by region in HS3. Both individuals showed lower T_{calf} and higher T_{chest} than any other T_{sk} region. The maximum difference between T_{calf} and T_{chest} can be 4°C; however, the regional T_{sk} responses to heat stress during the experiment were very similar.

Figure 6a. The distributions of measured skin temperatures by different regions and ICDA predictions in one individual (SN2) from HS3: Example 1.
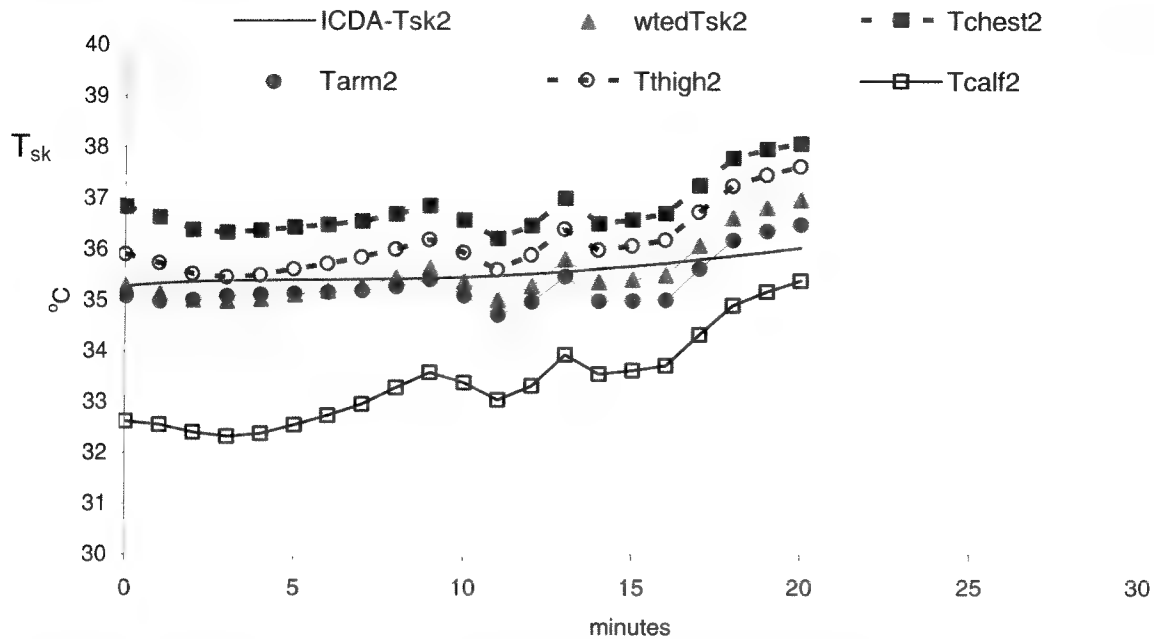
Figure 6b. The distributions of measured skin temperatures by different regions and ICDA predictions in one individual (SN5) from HS3: Example 2.
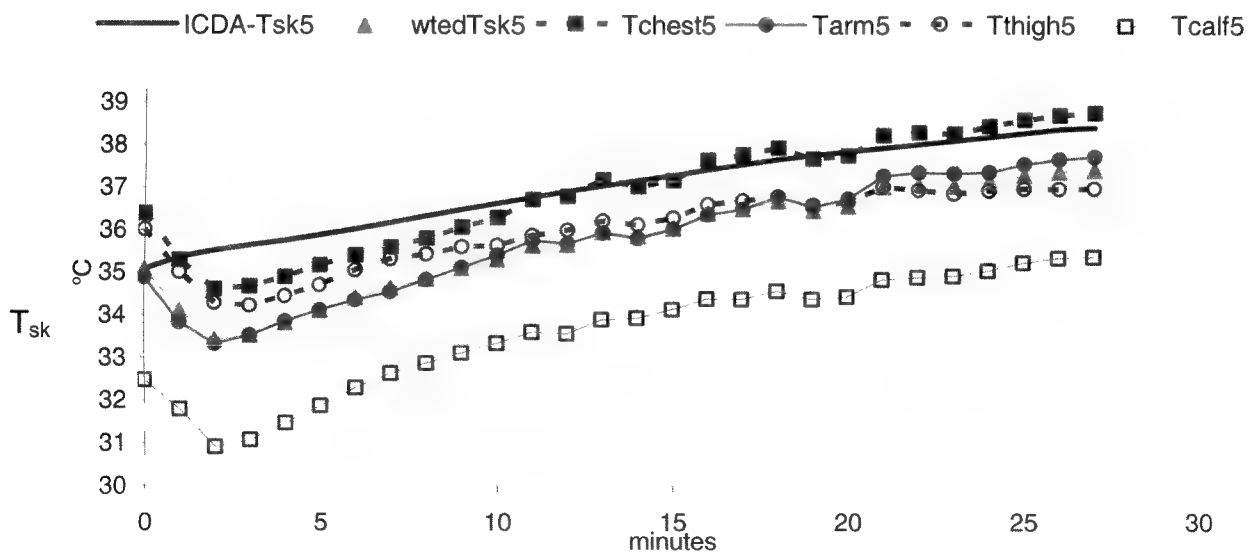
SWEAT RATES

Measured sweat rate (SR) data from HS1 and HS3 were available. SR in both studies was calculated from difference in body weight and associated weights (e.g., clothing) before and after work. Summaries of individual comparisons between measured and ICDA predicted SR for HS1 and HS3 are summarized in Tables 2 and 3, respectively. For HS1, the grand mean of SR predicted by ICDA (3.23 g/min) was not statistically different from measured value of SR (3.13 g/min), using a paired t-test ($p < 0.05$).

Table 2. Subject and group comparisons between measured Sweat Rates (SR) and predicted Sweat Rates (SR) for HS1.

Subject ID	lab SR (g/min)	ICDA SR (g/min)
1	3.71	2.39
2	3.44	4.03
3	1.57	2.38
4	3.17	4.35
5	3.17	2.70
6	3.97	3.06
7	2.64	2.90
8	2.77	3.37
9	3.71	3.92
MEAN	3.13	3.23
STDEV	0.73	0.73

In comparison to HS1, greater individual variability in SR was observed under the more strenuous heat conditions of HS3. ICDA SR predictions in HS3 varied by individual: similar SR predictions to measured SR (ΔSR < 1.2 g/min) were observed in three of eight individuals, while Δ SR in the rest of subjects varied between 1.2 and 6.3 g/min. Using a paired t-test ($p < 0.05$), mean values of measured and ICDA predicted SR were not statistically different for HS3. However, despite the favorable results for mean comparisons, individual variation for SR will need to be carefully considered for future predictions.

Table 3. Subject and group comparisons between measured Sweat Rates (SR) and predicted SR in HS3

Subject ID	lab SR (g/min)	ICDA SR (g/min)
1	8.83	3.01
2	9.07	3.64
3	7.19	6.69
4	5.28	10.16
5	12.66	12.46
6	11.95	13.84
7	14.33	8.04
8	12.55	11.41
MEAN	10.23	8.66
STDEV	3.12	4.01

DISCUSSION

The ICDA model, derived from a minimum number of non-invasive inputs, was designed primarily for screening physiological responses of deployed Soldiers assigned for long-hour multiple tasks. The initial analysis of this simple model yielded promising results for predicting the thermal status of Soldiers during heat stress. The ICDA predictions for T_{cr} were within an acceptable range of ± 1SD for non-heat acclimated volunteers when they were exposed to moderately stressful heat levels of 27°C/50%RH. However, under more stressful conditions, the ICDA predictions were better for heat-acclimated individuals than non heat-acclimated individuals. Initially predictions showed T_{cr} increasing faster than measured T_{cr} in heat-acclimated Soldiers. However, by the end of exercise, T_{cr} predictions were more accurate. Under heat stress wearing protective garments, the ICDA predictions were close to measured T_{cr}, although error estimates were larger when sample sizes were smaller. An option to improve the simulation for more diversified populations (e.g., non-acclimated persons, different fitness, and civilian occupations) could be added if that is desirable.

Predicted values for T_{sk} were not as accurate as T_{cr} predictions. This may be due in part, to between and within individual variability, and differences between the regions represented by different T_{sk} measurement sites. This trend seems to be especially true when the environmental temperature was lower than measured T_{sk}. The variability between measurement sites was less when subjects wore protective garments or when working in a hot-humid environment. Before more modeling development, there should be agreement on the best, most representative sites for measurement of T_{sk} to accommodate variability among individuals, clothing, environment, and operations.

Two heat studies (HS1, HS3) allowed comparison of measured SR to the ICDA predicted SR. When the heat stress was less strenuous, the mean change (Δ) in SR was 0.1 g/min. When the heat stress was more strenuous, the Δ in SR was greater. Although the mean predicted SR was not statistically different from the measured SR, prediction errors increased when individual variation in SR was increased. This may indicate that the estimate of M, based solely on HR, may not be adequate for accurate physiological predictions. For instance, predicted SR of two subjects in HS3 was lower than measured SR because of the high resting HR. As a result, a lower HR ratio was used to estimate lower M when T_a was constant. In these studies, resting HR was determined at rest or sitting at the beginning of the studies or lowest HR during the studies. It is possible that initial HRs were caused by anxiety, initial discomfort, or other physical or psychological factors, and were higher than under "true" neutral resting conditions. The affects of using a subjects' "true" resting HR on the calculated value of M need to be carefully considered.

Estimates of M from HR obtained using non-invasive methods are convenient for Soldiers who may be required to perform different tasks over many hours or even days. Normally, Soldiers deploying to regions known for extreme heat will be acclimatized during training for maximizing their performance and prevention from heat-related injuries. As the ICDA was primarily developed for heat acclimated Soldiers, predictions

of Soldiers' physiological status using the current version of ICDA will be more accurate for acclimated individuals. Although the present version of ICDA showed promising results with study data for some physiological parameters, further study, analysis, validation and improvements are recommended.

CONCLUSIONS

The human simulation computer program ICDA has been validated to estimate T_{cr}, T_{sk}, and SR using HR, environmental parameters and the Soldier's anthropological characteristics. The predictions were compared to measured values from three laboratory heat studies. Overall the simulation predictions of T_{cr} agreed well with the measured values for heat acclimatized Soldiers. The agreement for T_{sk} and SR was less accurate than T_{cr} and varied with clothing, environment, activity and individual differences, and should be evaluated further. Additional future experience with ICDA during field training situations will lead to further assessment, confidence, and possible improvements in application and hardware.

The ICDA real time physiological monitoring system was created for the narrow specialized application of trained heat acclimated Soldiers ready for deployment to a hot environment. However the system can be adapted for more variation in fitness, heat acclimation, body mass, age and other characteristics for application to more diverse groups of population and environment.

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A documented listing of the basic ICDA model described in the introduction and used in the verification follows. It is slightly different from the real time simulator on the Soldier in that measured input is entered through a keyboard rather than directly from the sensor system. Also the specified measurement interval is not driven by a clock in this case so the measured values can be keyboard entered at operators pace. Following the program instructions an example of the output is given.

```
/* Origin: BBMD @ USARIEM
Authors: Berglund and Yokota
Date: 6/30/05
File:  IC-DA-C-RT_Beta_steppedNonClockedInputs6_30_05

This simulates the real time thermal physiological responses(Tc,Tsk,waterLoss,skin wettedess, PSIc)
from real time inputs of measured HR, environmental parameters(Ta,MRT,RH,V) with constant personal
properties(ht,wt) and clothing.

The interval (in seconds) between measurements is adjustable. Enter 0 for the default interval of 60
seconds. In this program version the input interval is not controlled by a clock.
Measurements values are entered through key board at these intervals. The measurement interval is also
the model's integration interval.

Metabolism is expressed by dimenionless relative metabolism term (met) where met=actual
metabolism/resting metabolism. Met is estimated in this program from heart rate(HR) and air
temperature(Ta). intrinsic clo is thermal resistance from skin to outer layer of clothing in clo units.
MRT= mean radiant temperature.  V=air speed. */

#include <assert.h>
#include <stdio.h>
#include <math.h>
#include <ctype.h>

#define TTSK 33.7    //°C
#define TTCR 36.8    //°C
#define TTBM 36.49   // TTBM=.9*TTCR+.1*TTSK =36.49
#define CSW 170.     // g/(h m^2 °C)
#define CDIL 50.     // CDIL 200 super athlete, 50 average person
#define CSTR .5      //  1/°C
#define SKBFN 6.3    // liters/(h m^2)
#define Skbfmax 90.  // conservative could be higher for fit person
#define Skbfmin 2.   //Liters/(h m^2)
#define CMIN 5.28    // w/(m^2 °C)
#define CB 1.163     // wh/(L °C)
#define WpMet 58.1   //  w/(m2*met)
#define LR 2.2       //Lewis relation

void OutputHeader();
double SatVapPres(double T);
double Clot(int code, double V);     //total clo from skin to environment
double VRes(int code, double V);     // total vapor resistance from skin to environment
double Convection(double met, double V);    //convective heat transfer coefficient
double Respiration(double Rm, double Ta, double Pa,double* Wres); //respiratory heat loss
```

```c
double SkinBloodFlow(double Tc, double Tsk);
double DuBoisSkinArea(double Wt, double Ht);   //surface area of body
double MetT(double HR,double HRrest,double T);
double Alpha(double Skbf);                 // fraction of body that is skin
double Sweat(double Tc, double Tsk,double alpha);
double Core(double Tc,double Tsk,double met,double Res,double* hfcsk, double skbf,double* Rm);
double Skin(double wet,double Dry,double Emax,double* hfcsk);
double MoranPSI(double Tc,double Tco,double HR,double HRrest);   //heat stress index

int main (void){
    int step, HrTimeStep,code;double Ta,Tanew,MRT,MRTnew,RH,RHnew,Pa,Psk,Tcl,To,V,Vkm,Vnew;
    double hc,he,hr,met,Ht,Wt,Adu,Wres, drip,DT,DTs,ExTime;
    double wet,Tsk,Tsko,Tc,Tco,Rm,clo,FACL,Dry,Fpcl,PSIc;
    double Emax,Esk,Edif,Res,Skbf,HRrest,HR,HRnew,alpha,Regsw,Ersw;
    double heatFlowCoreToSkin,HSCR,HSSK,TCCR,TCSK,Rcl,Rbound,Rclt,Rpcl, Rpbound,Rpclt;
    double time,TIM,Duration,DurationM,CumulativeWaterLossPsqm;
    doubleCumulativeWaterLoss,CWLL,RateOfTotalWaterLossPsqm, RateOfTotalWaterLoss,Wdif;

    TIM=0; step=0; time =0; HR=0; HRrest=0; DTs=0;ExTime=0; HrTimeStep=0;

    printf("Enter interval between measurements in seconds(0 for default of 60 seconds):DTs  ");
    scanf("%lf",&DTs);
    if (DTs<=0)
        DTs=60;
    DT=DTs/(60*60); //DT in hrs
    printf("Enter intrinsic clo or -1 if unknown: clo  ");
    scanf("%lf",&clo);
    code=0;
    if (clo<0){
        printf(" Codes of manikin tested clothing types available for simulation: \n 1  HWBDU  \n 2
        APFU(SHTS+T) \n 3  Protective Garment(MOPP4) \n Enter Code: code ");
        scanf ("%d",&code);      }
    printf("Enter subject's weight(kg),height(m)(or 0's if unknown): Wt Ht ");/* inserts default values of
    70kg,1.72m */
    scanf("%lf%lf",&Wt,&Ht);
    if (Wt<=0)
        Wt=72.8;
    if (Ht<=0)
        Ht=1.72;
    printf("Enter subject's resting HR)(or 0's if unknown):HRrest ");/* inserts default values of 70 if HRrest
    are  zero */
    scanf("%lf",&HRrest);
    if (HRrest<=0)
        HRrest=70;
    Adu=DuBoisSkinArea(Wt,Ht); //m^2
    printf("Enter initial physiology (or 0's if unknown): Tsk Tc ");/* inserts  default values if Tsk,Tcr are
    zero's */
    scanf("%lf%lf",&Tsk,&Tc);
    if (Tsk <=0){
        Tsk=33; Tsko=Tsk; }
    else
        Tsko=Tsk;
    if (Tc <=0){
        Tc=36.9; Tco=Tc; }
    else
        Tco=Tc;
```

```c
        wet=.06;
        printf("Enter duration(min): ");    //may wish to delete duration for real applications

        scanf("%lf",&DurationM);
        Duration=DurationM/60.;            //hr
        printf("Enter HR Ta(C) MRT(C) RH(percent) V(km/h) :  ");
        scanf("%lf%lf%lf%lf%lf",&HR,&Ta,&MRT,&RH,&Vkm);
        V =Vkm*1000/(60*60); // convert km/h to m/s
        met=MetT(HR,HRrest,Ta); //from Berglund 30th ACEMB,1977
        OutputHeader();

        Pa=RH*SatVapPres(Ta)/100;    // vapor press Torr
        Skbf=SkinBloodFlow(Tc,Tsk); //Liters/(h m^2)
        alpha=Alpha(Skbf);          //skin fraction of body =Wtsk/Wt
        Regsw=Sweat(Tc,Tsk,alpha);  // g/(h m^2)
        CumulativeWaterLossPsqm=0;
        CumulativeWaterLoss=0;
        drip=0; CWLL=0;
        hc = Convection(met,V); // convection
        hr=4.5; //radiation watts/(m^2 K)
        To=(hc*Ta + hr*MRT)/(hc+hr);
        if (code==0) {
            FACL=1.0+.2*clo; // surface area of clothing relative to Adu
            Rcl=.155*clo; // clothing thermal resistance m^2 C/watts
            Rbound=1/((hr+hc)*FACL); //  boundary layer thermal resistance m^2 C/watts
            Rclt=Rcl+Rbound;
            Rpcl= .153181*clo;        }
        else {
            FACL=1.2;               //guess with clo=1
            Rclt=.155*Clot(code,V);
            Rbound=1/((hr+hc)*FACL); //  boundary layer thermal resistance m^2 C/watts
            Rcl=Rclt-Rbound;
            clo=Rcl/.155;  //estimate of uniform's intrinsic clo
            FACL=1+.2*clo; }
        Dry=(Tsk-To)/(Rclt);
        Tcl = To +Dry/(FACL*(hr+hc));

        PSIc=MoranPSI( Tc,Tco, HR,  HRrest);
        printf("%5.1f %5.1f %5.1f%4.0f %5.2f %5.2f %5.2f %5.2f %5.2f %5.2f%4.0f %5.3f %5.2f \n
        ",ExTime,Ta,MRT,RH,Vkm,Tc,Tsk,met,Regsw/60*Adu,wet,HR,CWLL,PSIc);
        time+=Duration;
        while (TIM<=time) { // thermo-physiology loop
// dry and evaporative heat transfer
            Skbf=SkinBloodFlow(Tc,Tsk);        //Liters/(h m^2)
            Psk=SatVapPres(Tsk);    // vapor press Torr (mmHg)
            Rm= WpMet*met;          // watts/(m^2)
            hc = Convection(met,V);   // convection */
            he=2.2*hc;                      // evaporation   watts/(m^2 Torr)
            hr=4*.725*(5.67E-08)*pow(((Tcl+To)/2+273),3); // corrected hr
            To=(hc*Ta + hr*MRT)/(hc+hr);
            if (code==0)        {
                Fpcl=1/(1+.153181*he*FACL*clo);   //Berglund 1981, for IL=.45
                Rpbound=1/(he*FACL);
                Rpclt=Rpcl+Rpbound;
                Rbound=1/((hc+hr)*FACL);
                Rclt=Rbound+Rcl;        }
```

```c
    else {
        Rpclt=VRes(code,V); }
    Emax=(Psk-Pa)/Rpclt;
    Dry=(Tsk-To)/(Rclt);
    Tcl = To +Dry/(FACL*(hr+hc));

// Thermal Physiology
    Res = Respiration(Rm,Ta,Pa,&Wres);
    alpha=Alpha(Skbf);
    Regsw=Sweat(Tc,Tsk,alpha);          // g/(h m^2)
    Ersw=.68*Regsw;                     // watts/m^2
    Edif = (1-wet)*.06*Emax;            // diffusion through dry skin
    Wdif=Edif/.68;                      // g/(h m^2)
    Esk=(Wdif+Regsw)*.68;               // energy lost by evaporation from and diffusion through  skin.
    wet=Esk/Emax;
    if (wet>=1){
        wet=1;
        drip=(Wdif+Regsw)-(Emax/.68); }     // wasted sweat driping from skin g/(hm^2)
    else {
        drip=0; }
    Esk=(.06+.94*wet)*Emax;
    RateOfTotalWaterLossPsqm=Regsw+Wres+Wdif;           // g/(h m^2)
     RateOfTotalWaterLoss=RateOfTotalWaterLossPsqm*Adu;   //g/h m^2)
    CumulativeWaterLossPsqm=CumulativeWaterLossPsqm+RateOfTotalWaterLossPsqm*DT;
    CumulativeWaterLoss=CumulativeWaterLoss+RateOfTotalWaterLoss*DT;
    CWLL=CumulativeWaterLoss/1000;                          //Liters
    PSIc=MoranPSI( Tc,Tco, HR,  HRrest);
    HSCR = Core(Tc,Tsk,met,Res,&heatFlowCoreToSkin,Skbf,&Rm);
    HSSK = Skin(wet,Dry,Emax,&heatFlowCoreToSkin);

/* thermal capacity */
    TCCR=.97*(1-alpha)*Wt;
    TCSK=.97*alpha*Wt;

/* stepwise integration */
    Tc +=HSCR*Adu/TCCR*DT;
    Tsk +=HSSK*Adu/TCSK*DT;
    TIM +=DT;
    ExTime+=DT*60;  //min
    printf("Enter HR Ta MRT RH V or 0 for any unchanged parameter:  ");
    scanf("%lf%lf%lf%lf%lf",&HRnew,&Tanew,&MRTnew,&RHnew,&Vnew);
    if (HRnew>0)
        HR=HRnew;
    If (Tanew>0)
        Ta=Tanew;
    If (MRTnew>0)
        MRT=MRTnew;
    If (RHnew>0)
        RH=RHnew;
    If (Vnew>0)          {
        Vkm=Vnew;                   //km/h
        V=Vkm*1000/(60*60); }     //m/s
    met=MetT(HR,HRrest,Ta);
    printf("%5.0f %5.1f %5.1f%4.0f %5.2f %5.2f %5.2f %5.2f %5.2f %5.2f%4.0f%5.3f%5.2f\n
    ",ExTime,Ta,MRT,RH,Vkm,Tc,Tsk,met,Regsw/60*Adu,wet,HR,CWLL,PSIc);
}
```

```c
    return 0 ;
}

void OutputHeader() {
    printf("\nmin   Ta   Tr  RH  V   Tc   Tsk   met  sw   wet  HR CWLoss PSIc\n");
    printf("      C    C       km/h C    C        g/min      bpm  L\n");
}

double SatVapPres(double T) {
    double Pst;
    Pst = exp(18.6686-(4030.183/(T+235.)));          //mmhg
    return Pst;
}

double Clot(int code, double V) {
    double A1=0,B=0;
    switch (code) {
        case 1:          //HWBDU
                A1=1.08; B=-0.27;  break;
        case 2:          //APFU(SHTS+T)
                A1=0.51; B=-0.39;  break;
        case 3:          //Protective Garment(MOPP4)
                A1=1.7; B=-0.16;  break;
        default:printf("Illegal clothing code,must be an integer between 1 and 3  ");break; }
    return A1*pow(V,B);
}

double VRes(int code, double V) {
    double Ai1=0,Bi=0;
    switch (code) {
        case 1:          //HWBDU
                Ai1=0.47;  Bi=0.41;  break;
        case 2:          //APFU(SHTS+T)
                Ai1=1.41;  Bi=0.58;       break;
        case 3:          //Protective Garment(MOPP4)
                Ai1=0.17;   Bi=0.31;  break;
        default:printf("Illegal clothing code,must be an integer between 1 and 3 ");  break; }
    return 0.155/(LR* Ai1*pow(V,Bi));
}

double Convection(double met,double V) {
    double CHCA, CHCV, CHCmin, hc; CHCmin = 3.0;
    if (met>=1.1) {
        CHCA = 5.66*pow((met - 0.85),0.39);          // hc due to activity
    else {
        CHCA = 5.66*pow((1. - 0.85),0.39); }          // hc due to activity
    }
    CHCV = 8.6*pow(V,0.53);                              // hc due to air speed V in m/s */
    if (CHCV >= CHCmin)                     ;
    else
        (CHCV = CHCmin);
    if (CHCV >= CHCA)
        hc = CHCV;
    else
        hc = CHCA;
```

```c
    return hc;
}

double Respiration(double Rm, double Ta, double Pa,double*Wres){
    double Res,Eres,Cres;
    Eres = 0.0023*Rm*(44.-Pa);              // watts/m2
    Cres = 0.0014*Rm*(34.-Ta);              // watts/m2
    *Wres=Eres/.68;                         //  g/(h m^2) */
    Res = Eres + Cres;
    return Res;
}

double DuBoisSkinArea(double Wt, double Ht) {
    double Adu; /* m^2 */
    Adu=0.202*pow(Wt,0.425)*pow(Ht,0.725);   // Wt weight in kg, Ht height in m.
    return Adu;
}

double MetT(double HR,double HRrest,double T) {   // Berglund,30th ACEMB 1977
    double met,HRratio;  /* applicable:20<=T<=40, 0.6clo, v~=1.25m/s, 1.2<+HRratio<=2.1,Tdp<=20C*/
    HRratio=HR/HRrest;
    if (HRratio>=1.2) {
        if (T>=20)
                met=0.68+4.69*(HRratio -1)- 0.052*(HRratio-1)*(T-20);
        else
                met=0.68+4.69*(HRratio -1); }
    else {
        met=HRratio;    }
    return met;
}

double Alpha(double Skbf) {
    double alpha;
    alpha=0.04177+.74518/(Skbf+0.585417);
    return alpha;
}

double Sweat(double Tc, double Tsk, double alpha) {
    double regsw, Tmb;
    regsw=0;
    Tmb=(1-alpha)*Tc + alpha*Tsk;
    if ((Tmb>TTBM)&&(Tsk>TTSK))
        regsw=CSW*(Tmb-TTBM)*exp((Tsk-TTSK)/10.7);
    else if ((Tmb>TTBM)&&(Tsk<=TTSK))
        regsw=CSW*(Tmb-TTBM);
    if (regsw>667)                          // max sweat rate limit
        regsw=667;                          // regsw_max=667g/(h m^2)=11.1g/(min m^2)!=20g/(min m^2)
    return regsw;                           //g/(h m^2)
}

double SkinBloodFlow(double Tc, double Tsk) {
    double Colds=0;
    double Skbf, WarmC=0;
    if (Tsk<TTSK)
        Colds=TTSK-Tsk;
    if (Tc>TTCR)
```

```
            WarmC=Tc-TTCR;
        Skbf=(SKBFN+CDIL*WarmC)/(1+CSTR*Colds);        // Liters/(h m^2)
        if (Skbf>Skbfmax)
            Skbf= Skbfmax;
        if (Skbf<Skbfmin)
            Skbf= Skbfmin;
        return Skbf;                                    // L/(h m^2)
}

    double Core(double Tc,double Tsk,double met,double Res,double*heatFlowCoreToSkin, double Skbf,
    double*Rm) {
        double Rmet,Hfcrsk,HSCR;
        Hfcrsk=(CMIN+CB*Skbf)*(Tc-Tsk);        // watts/m^2
        Rmet = 58.2*met ;                       // metabolic heat produced watts/m^2.
        HSCR=Rmet-Hfcrsk-Res;                   // rate of heat storage in core  watts/m^2
        *heatFlowCoreToSkin=Hfcrsk;
        *Rm=Rmet;
        return HSCR;
}

    double Skin(double wet,double Dry,double Emax,double*heatFlowCoreToSkin ) {
        double Esw,Ediff,Esk,HSSK;
        Esw=wet*Emax;
        Ediff=.06*(1-wet)*Emax;
        Esk=Esw+Ediff;
        HSSK=*heatFlowCoreToSkin-Dry-Esk;        // rate of heat storage in skin watts/m^2
        return HSSK;
}

    double MoranPSI(double Tc,double Tco,double HR, double HRrest){
        double PSI;
        PSI=5*((Tc-Tco)/(39.5-Tco)+(HR-HRrest)/(180-HRrest));
        return PSI;
}
/* This is the End */


/* output is pasted below
Enter interval between measurements in seconds(0 for default of 60 seconds):DTs  0
Enter intrinsic clo or -1 if unknown: clo  -1
Codes of manikin tested clothing types available for simulation:
  1  HWBDU
  2  APFU(SHTS+T)
  3  Protective Garment(MOPP4)
Enter Code: code 2

Enter subject's weight(kg),height(m)(or 0's if unknown): Wt Ht 0 0
Enter subject's resting HR)(or 0's if unknown):HRrest  0
Enter initial physiology (or 0's if unknown): Tsk Tc 0 0
Enter duration(min):  10
Enter HR Ta(C) MRT(C) RH(percent) V(km/h) :  75 27 27 75 4

min  Ta  Tr  RH  V   Tc    Tsk   met  sw   wet  HR CWLoss PSIc
     C   C      km/h C     C          g/min     bpm  L
 0.0 27.0 27.0 75  4.00 36.90 33.00 1.07  0.00 0.06 75 0.000 0.23
Enter HR Ta MRT RH V or 0 for any unchanged parameter:  90 0 0 0 0
```

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```
    1  27.0  27.0  75  4.00 36.90 32.78  1.92  0.00  0.06  90 0.001  0.23
Enter HR Ta MRT RH V or 0 for any unchanged parameter:  109 0 0 0 0
    2  27.0  27.0  75  4.00 36.92 32.58  3.09  0.00  0.06 109 0.002  0.91
Enter HR Ta MRT RH V or 0 for any unchanged parameter:  107 0 0 0 0
    3  27.0  27.0  75  4.00 36.98 32.41  2.97  0.00  0.06 107 0.004  1.82
Enter HR Ta MRT RH V or 0 for any unchanged parameter:  108 0 0 0 0
    4  27.0  27.0  75  4.00 37.02 32.27  3.03  0.00  0.06 108 0.005  1.83
Enter HR Ta MRT RH V or 0 for any unchanged parameter:  0 0 0 0 0
    5  27.0  27.0  75  4.00 37.06 32.16  3.03  0.00  0.06 108 0.006  1.96
Enter HR Ta MRT RH V or 0 for any unchanged parameter:  0 0 0 0 0
    6  27.0  27.0  75  4.00 37.10 32.06  3.03  0.26  0.07 108 0.008  2.04
Enter HR Ta MRT RH V or 0 for any unchanged parameter:  0 20 20 0 0
    7  20.0  20.0  75  4.00 37.13 31.98  3.23  0.48  0.09 108 0.010  2.11
Enter HR Ta MRT RH V or 0 for any unchanged parameter:  0 0 0 0 0
    8  20.0  20.0  75  4.00 37.17 31.51  3.23  0.68  0.10 108 0.012  2.17
Enter HR Ta MRT RH V or 0 for any unchanged parameter:  0 0 0 0 0
    9  20.0  20.0  75  4.00 37.20 31.12  3.23  0.52  0.09 108 0.013  2.24
Enter HR Ta MRT RH V or 0 for any unchanged parameter:  0 0 0 0 0
   10  20.0  20.0  75  4.00 37.23 30.81  3.23  0.43  0.09 108 0.015  2.30
Press any key to continue
*/
```
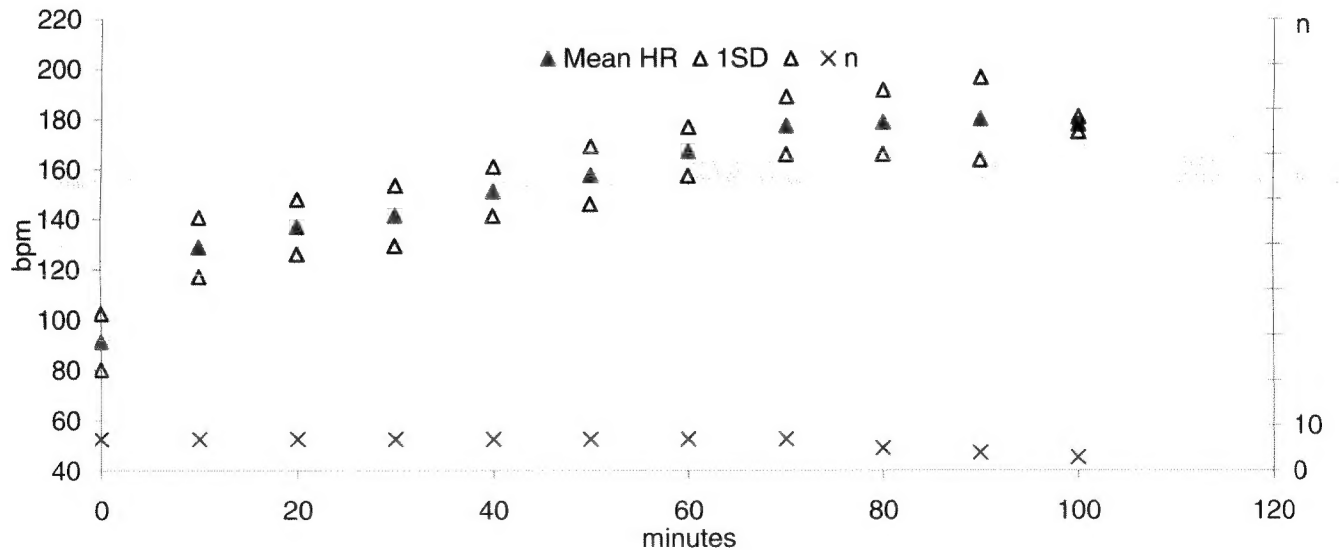
APPENDIX B

The mean HR and ±1SD from each study are displayed.
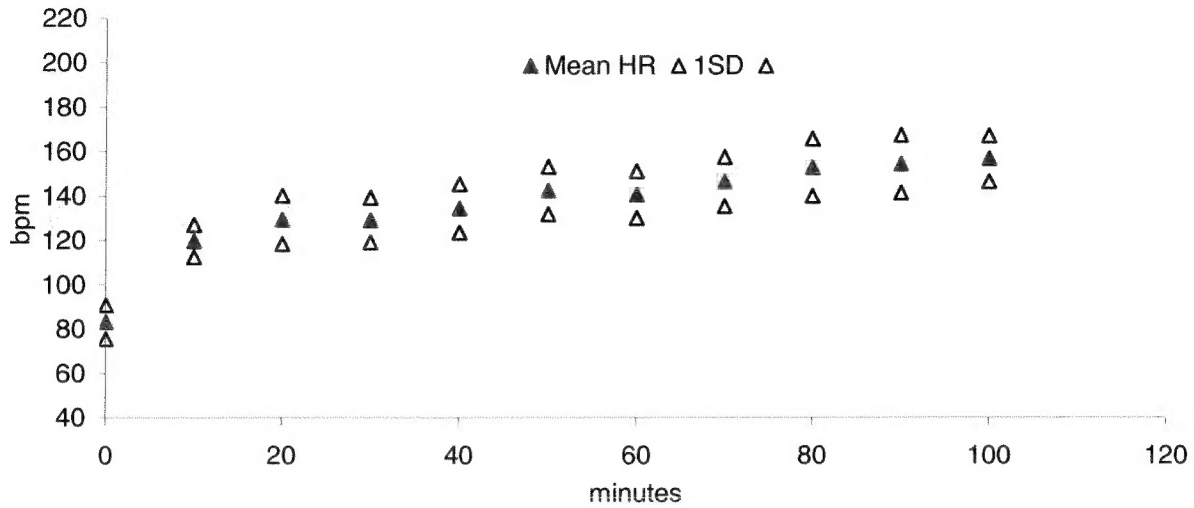
a. Heat Study 1 (27°C, 75%; HWBDU; n=9)
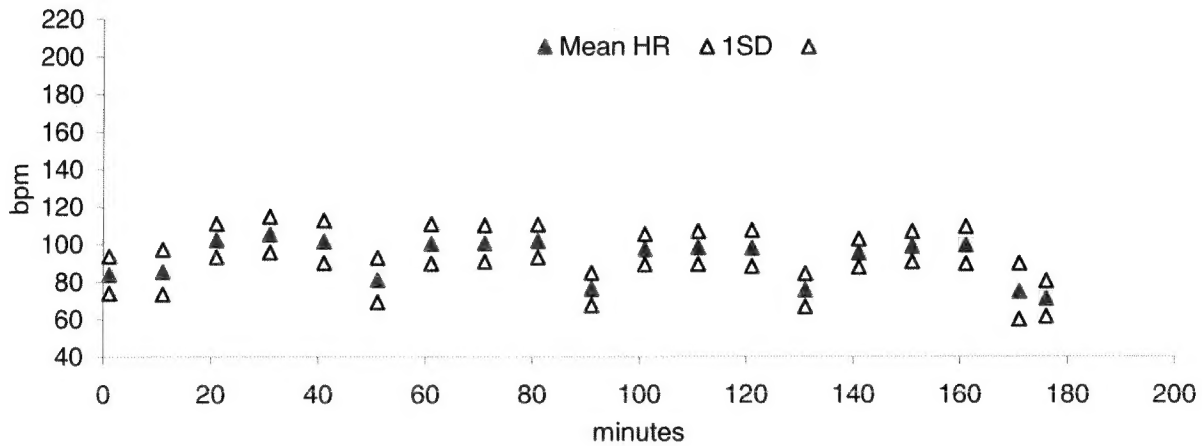
b. Heat Study 2 (day1 – non acclimation state; 49°C, 18%; APFU; n≤7)

c. Heat Study 2 (day2 – acclimation state; 49°C, 18%; APFU; n=5)

d. Heat Study 3 (35°C, 45%; protective garment; n≤8)